in increasing friction (the mechanical equivalent of electrical resistance). The deliberate increase of friction is, however, very wasteful of power, and is liable to lead to inconsistency in action.

Waste of power can be avoided by providing a heavy flywheel connected to the driven member by a friction drive. This provides the desired friction when acceleration occurs, but at other times the flywheel rotates with the driven member without slipping.

This method has been adopted with some success on low-power drives for data transmission, but the flywheel would be impracticably large if used with a heavy aerial.

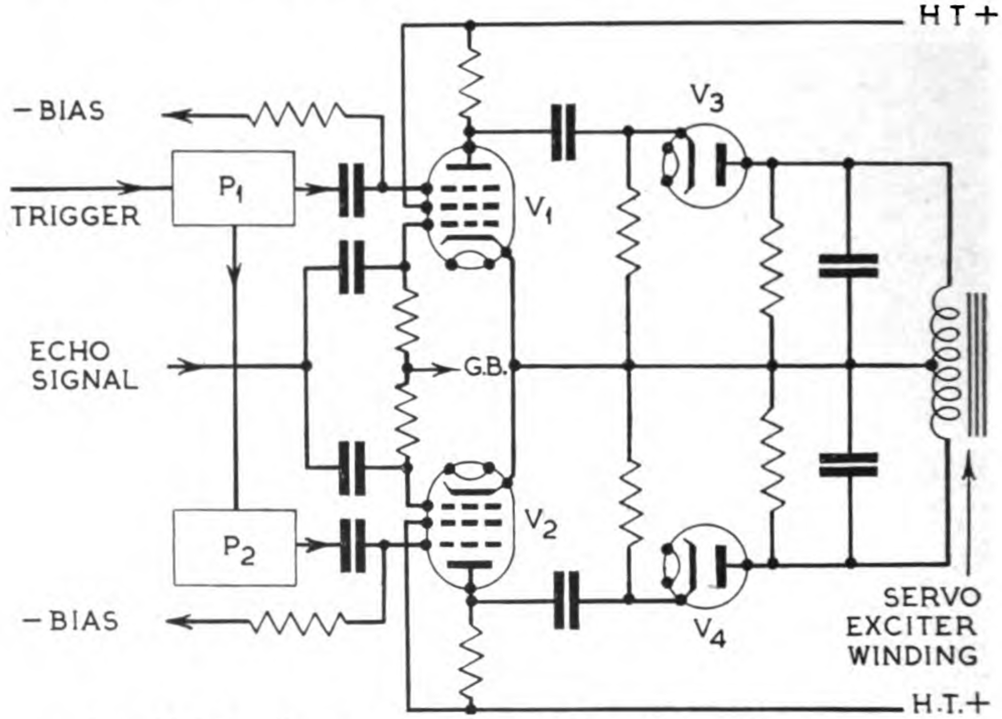

Fig. 11.10.—Automatic Following—Basic Circuit.

Another method is to connect a tachometer (a small d.c. permanent-magnet generator giving an output voltage proportional to speed) to the driven member and feed the output of this to the control mechanism in opposition to the error signal. This is an electrical method of producing a retarding force proportional to speed.

The foregoing expedients are, however, only partial solutions. A servo system is a power source and can, in certain circumstances, hunt even if the precautions detailed above are taken. A simple example will suffice. Suppose there is a time lag in the response of the servo system. When the driven member reaches its correct position, it *must* overshoot it, because a short time will elapse before it "knows it has got there". This overshoot is then corrected, and followed by one in the opposite direction, i.e. the system will continue to hunt.

This can be dealt with by using phase-shifting circuits which give a lead to the error signal at the frequency at which the system tends to oscillate, this lead cancelling the lag referred to above.

The problem is considerably more complicated than the short statement made here would imply, but space does not permit of fuller treatment.

The difficulties mentioned and the steps that must be taken to overcome them prevent a servo system from being absolutely accurate. For example, assuming steady rotation of an aerial, there will always be a small permanent positional error, and it is the aim of the designer to make this as small as possible.

Automatic Following

Fig. 11.10 shows the elements of a circuit that will enable a radar to follow automatically in range a selected target once it has been "put on" to that target by the operator.

Video echo signals are fed in parallel to two pentodes V_1 and V_2. P_1 and P_2 represent two gate-pulse-forming circuits which generate gate pulses, of length comparable with that of the echo. P_1 is triggered by a pulse from a range potentiometer, and P_2 is triggered by the trailing edge of the pulse from P_1. The result is two pulses displaced in time as shown in Fig. 11.11.

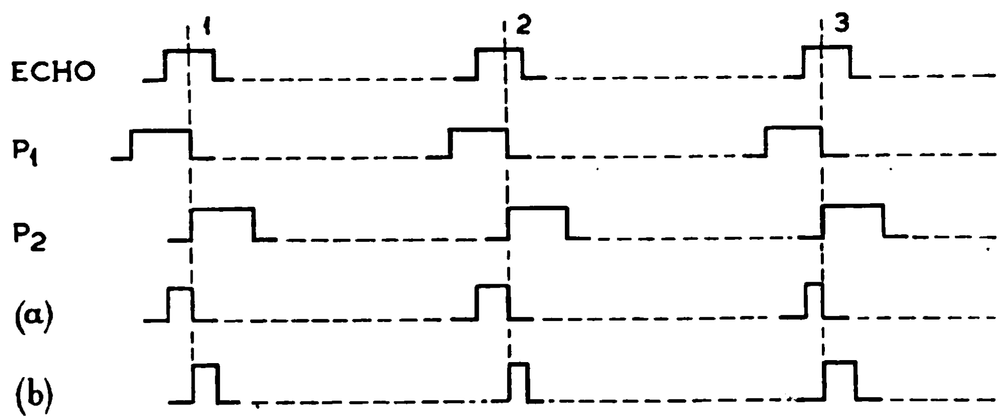

Fig. 11.11.—Automatic Following—Gate Pulses.

V_1 and V_2 are biased so that each conducts only when there is both a gate pulse and an echo pulse.

The outputs of V_1 and V_2 are passed through the diodes V_3 and V_4, and their difference is the error signal. This is applied to the field winding of a servo motor controlling the setting of the range potentiometer.

If the two gate pulses, whose position depends on the setting of the range potentiometer, are symmetrically disposed with respect to the echo signal, the error signal is zero; otherwise it is in a direction which alters the setting of the range potentiometer until the error is reduced substantially to zero.

Fig. 11.11 shows three cases corresponding respectively to zero error, echo early and echo late.

A magslip, geared to the slider of the range potentiometer, conveys the range information to the position at which it is required. As the first gate pulse must start before the instant at which the echo arrives, a "zero correction" must be made when setting up the slider or magslip initially.

Circuits for producing trigger and gate pulses are described in Chapter XV.

For following in bearing or elevation, an aerial system using split is used, the echo signals corresponding to the two béam positions being fed through gated circuits of the same general type as Fig. 11.10. The servo system then drives the aerial round until the outputs from the two halves of the circuit are equal. To avoid difficulty due to two targets being on the same bearing but at different ranges, it is desirable to provide an overriding gate circuit, controlled by the ranging circuit, which only allows echo signals from a target at the correct range to reach the auto-follow circuit.

The time constants of the output circuit can be made long enough to avoid losing the target during periods of momentary fading, but there must be a compromise between this facility and the required rapidity of response when the rate of change of range or bearing alters. It is also useful to provide the operator with a switch for cutting out the incoming signals when the visual display suggests that a stronger unwanted echo may take charge, or heavy clutter cause the wanted echo to be lost. Whilst this switch is open, the circuit carries on as during fading.

CHAPTER XV

CALIBRATOR AND STROBE CIRCUITS

THE length of the trace on a cathode-ray tube is too small to enable the range of a particular echo to be measured with any great degree of accuracy. For accurate ranging the null method described on page 134 may be used. Alternatively one part of the trace can be speeded up (as described on page 135) and a marker or markers, representing known ranges, added. The range of the wanted echo is then determined by reference to one or more markers.

The markers may be a series of calibrator pips, spaced at known equal intervals as in Fig. 15.1 (*a*), or a single marker or "strobe" may be produced. This may take the form of a step

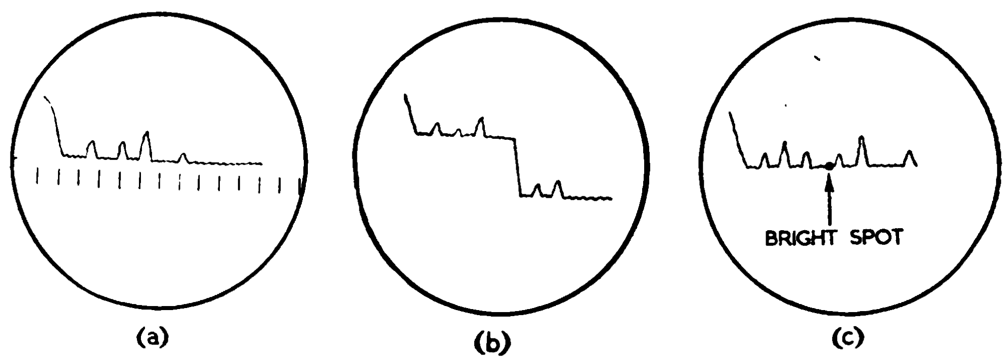

FIG. 15.1.—MARKERS OR STROBES.
(*a*) Calibration pips. (*b*) Step strobe. (*c*) Bright spot strobe.

[Fig. 15.1 (*b*)] or a bright spot [Fig. 15.1 (*c*)]. The former is usually easier to see, but is not applicable to the case of a P.P.I. To measure range, the strobe is moved until it is in line with the leading edge of the relevant echo, and the range is then read off a calibrated scale attached to the potentiometer controlling the position of the strobe along the timebase.

With a P.P.I. the bright spot strobe appears as a circle, concentric with the centre of the screen, and of radius proportional to the range.

A variation of the calibrator pip method consists of means for moving the whole series of pips, *en bloc*, along the trace by a known controllable amount. Any particular pip can then be aligned with a selected echo.

Circuits for Generating a Series of Calibrator Pips

The basic principle in producing calibrator pips is to make use of an oscillator of accurately controlled frequency, and

square and differentiate its output. The initial oscillation may be obtained from a crystal or from a "ringing circuit". An example of the latter is shown in Fig. 15.2.

In the quiescent state V_1 and V_2 are conducting, and V_3 is cut off by negative bias on its grid. When the transmitter fires, a negative-going square wave from a multivibrator controlled by the transmitter is applied to the grid of V_1, causing this valve to cut off. When this happens, the ringing circuit L_1C_1 starts to oscillate at its natural frequency. The oscillatory voltage, amplified if necessary, is applied to the grid of V_2 which it overdrives sufficiently to produce a square wave at the anode, the first half-cycle being positive. This is differentiated by C_2R_1 and a positive pip is produced at the grid, and

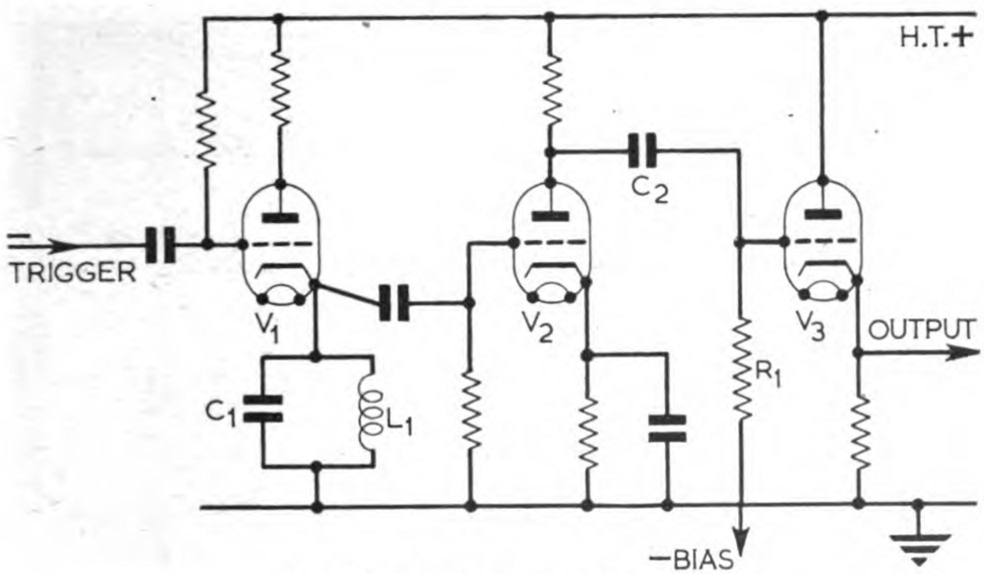

FIG. 15.2.—RINGING CIRCUIT.
For producing calibration pips.

therefore at the cathode also, of V_3 for every cycle of oscillation of the "ringing circuit".

The first pip is substantially coincident in time with the cutting off of V_1. The negative-going pips, occurring one half-cycle after the positives, have no effect since V_3 is normally cut off.

On the cessation of the negative input wave, the circuit reverts to its initial state.

The accuracy of circuits of this type depends on the maintenance of the natural frequency of the ringing circuit. For more accurate work a crystal may be used, either to check the tuning of the ringing circuit periodically, or to act as the initial source of oscillation.

Circuit of Fig. 15.3

In the quiescent state $V_1V_2V_3$ are conducting and V_4V_5 cut off by negative bias on their grids. At the beginning of the

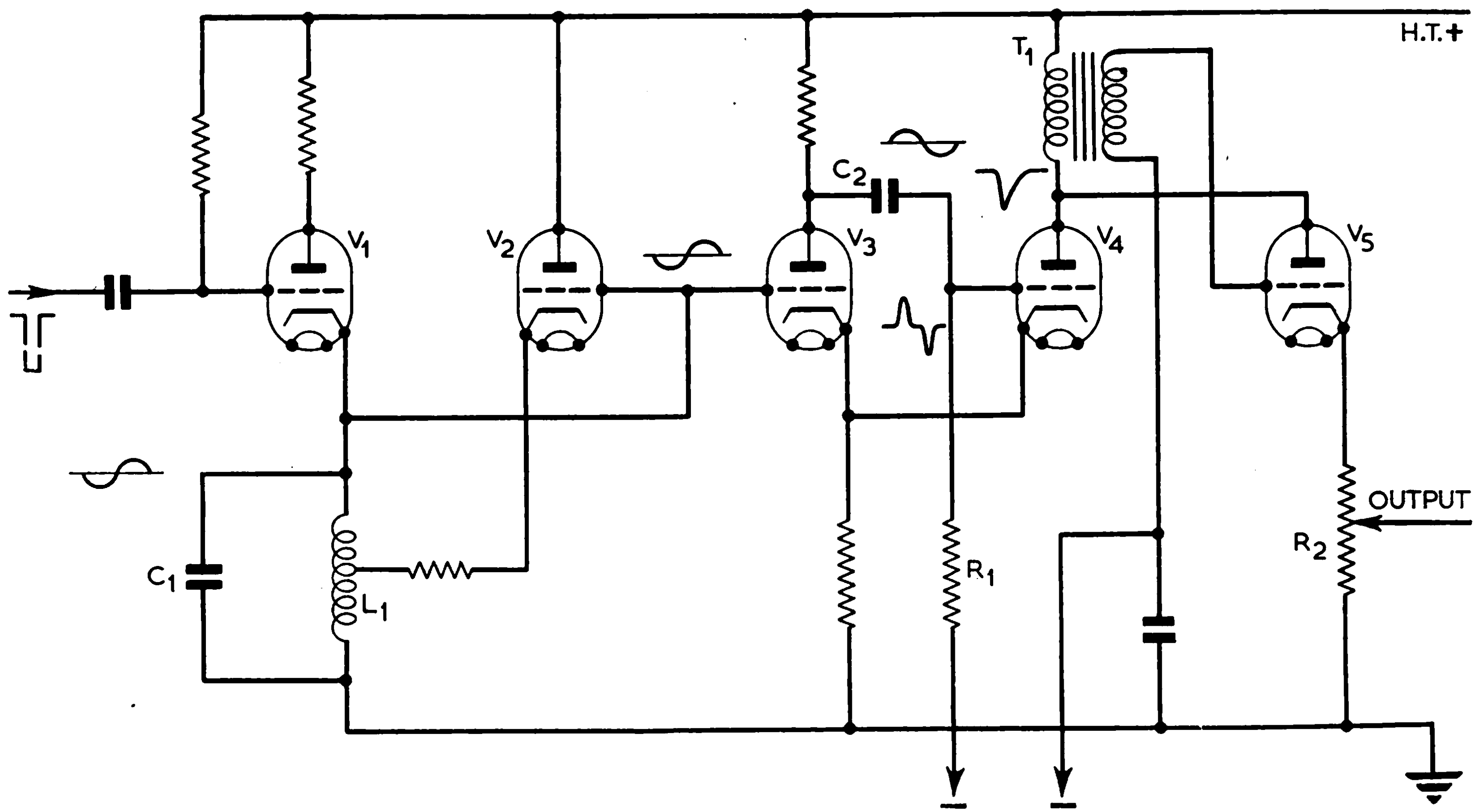

FIG. 15.3.—RINGING CIRCUIT USING BLOCKING OSCILLATOR.

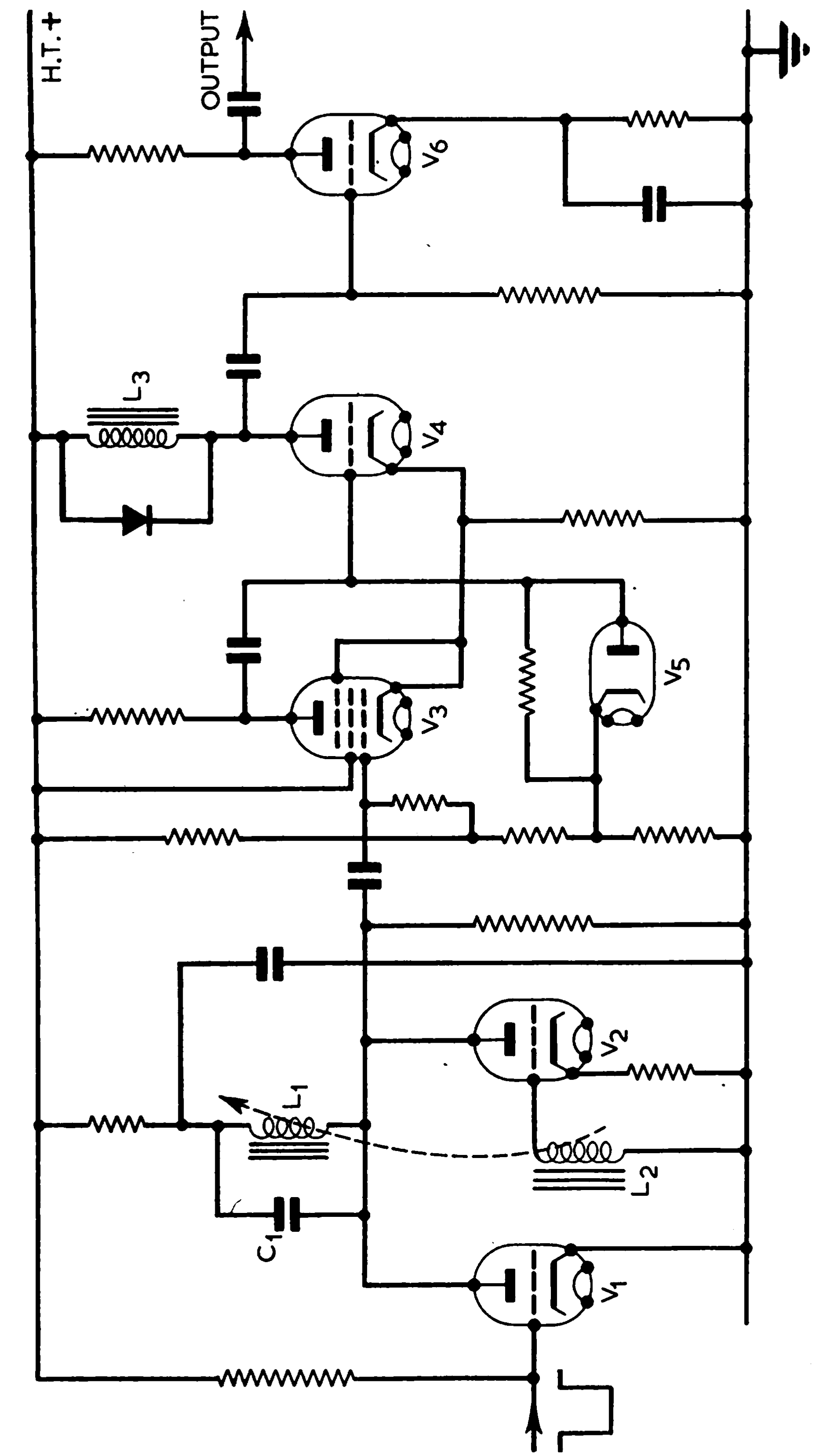

FIG. 15.4.—RINGING CIRCUIT.—ANOTHER EXAMPLE.

timebase sweep a negative switching wave cuts off V_1 and allows the circuit L_1C_1 to start ringing. The first half-cycle is negative going and cuts off V_3 and allows V_4 to conduct. V_3V_4 form a cathode-coupled flip-flop. T_1 and V_5 constitute a blocking oscillator which produces a sharp pulse of current in V_5. This provides the calibration pip, which is tapped off the cathode resistor R_2. The time constant of C_2 and R_1 is very short, and the flip-flop almost immediately reverts to its initial state, preventing the blocking oscillator from producing another pip until triggered again by the ringing circuit one cycle later. The second half-cycle of the ringing circuit, which is positive going, has no effect because V_3 is already conducting. The function of V_2 is to provide regeneration to prevent too rapid decay of the oscillation in L_1C_1 during the timebase sweep.

Circuit of Fig. 15.4

In the quiescent state $V_1V_2V_3V_6$ are conducting and V_4 is cut off. V_3 and V_4 form a cathode-coupled flip-flop. L_1C_1 form the ringing circuit, regeneration being provided by V_2L_2. The low resistance of V_1 when conducting prevents the ringing circuit from oscillating. A negative-going switching wave cuts off V_1 at the beginning of the timebase sweep, and L_1C_1 ring, the first half-cycle being positive going at the grid of V_3. Very soon after the beginning of the second half-cycle, which is negative, the flip-flop changes to its other state and V_4 begins to conduct. The presence of the crystal rectifier CR_1 across its anode load prevents any appreciable voltage from appearing at the grid of the output valve V_6. At the beginning of the third half-cycle, i.e. one cycle from the start, the flip-flop reverts to its initial state and V_4 cuts off, the interruption of the current in L_3 producing a negative calibration pip at the anode of V_6. Any tendency towards the production of a pip of opposite polarity following the wanted one, due to tendency of L_3 to oscillate with stray capacitance, is suppressed by the crystal rectifier.

This cycle of operations is repeated for every cycle of the ringing circuit. The diode V_5 limits the conduction of V_4 to a suitable value.

Use of Goniometer for moving Calibration Pips along Timebase

A goniometer consists of two pairs of fixed coils at right angles, and a search coil which can be rotated inside them, as shown diagrammatically in Fig. 15.5.

An alternating voltage from the ringing circuit, or other oscillator used for calibrating, is fed to the two sets of coils as shown, a resistance being included in each circuit, and a capacitance C in one. Let L be the inductance of each pair of coils, then if R and C are adjusted so that $L/C = 2R^2$ and $2\omega^2LC = 1$, where $\omega = 2\pi$ times the frequency, and R is the value of one added resistor plus one set of coils, the two sets

of fixed coils produce a rotating field of constant amplitude. The magnitude of the voltage induced in the search coil is independent of its angular position, but its phase is directly proportional to its angular displacement from some arbitrary zero. The goniometer therefore provides a means of obtaining a calibrator a.c. supply whose phase can be continuously varied. If the output of the search coil is amplified and fed to any of the calibrator circuits described above, the calibration pips can be moved along the timebase by rotating the coil. If a scale is attached, range can be read off by adjusting some particular pip to coincidence with the leading edge of the direct transmitter signal and then moving this pip along until it is aligned with the wanted echo.

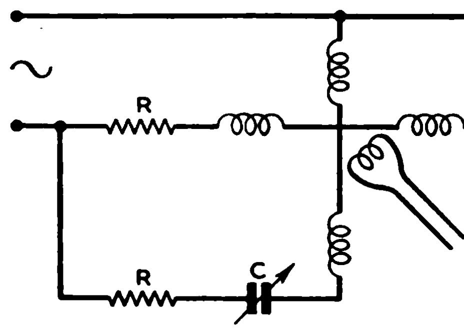

FIG. 15.5.—GONIOMETER. Used for moving calibration pips along timebase.

Normally the leading edge of the direct signal is not visible on the trace, but this difficulty can be overcome by arranging for the timebase to be triggered a few microseconds before the transmitter fires, or the zero can be set by means of an echo from a fixed object at known range.

If, as will often be the case, a timebase with a speeded-up portion or a strobe, or both, is used, the potentiometers governing the points at which these things occur can be geared to the spindle of the goniometer so that they automatically occur at the correct places.

Crystal-controlled Calibrator

When greater accuracy is required, the ringing circuit of the calibrators described above can be replaced by a crystal-controlled oscillator.

Since the first calibrator pip must coincide with the start of the timebase sweep it is necessary either to pulse the crystal, i.e. start it oscillating, at the beginning of each sweep and stop it at the end, or else arrange for the sweep to start and the transmitter to fire at the same time as a pip.

Although pulsed crystal circuits are possible, their adjustment presents some difficulty, and the second alternative is generally used.

If, as will generally be the case, the p.r.f. of the system is governed by the frequency of the a.c. power supply, the circuit shown in Fig. 15.6 can be used.

V_3 is a thyratron and V_4 a pentode normally cut off on both its control and suppressor grids. During the half-cycle when the upper end of T_1 is positive, C_1 is charged through V_1 and

R_1. V_2 is held off because its grid is negative due to being connected to the lower end of the transformer, whose winding is earthed at some intermediate point. Calibrator pips, from the crystal circuit, are fed through V_3 to the control grid of V_4, but have no effect because this valve is cut off on its suppressor.

Shortly before the end of the half-cycle, when the grid of the thyratron is approaching zero voltage and going positive, this valve fires, and the current through R_2 raises the potential of the suppressor of V_4, allowing this valve to conduct when pips are applied to its control grid.

Negative-going calibrator pips are therefore produced at the

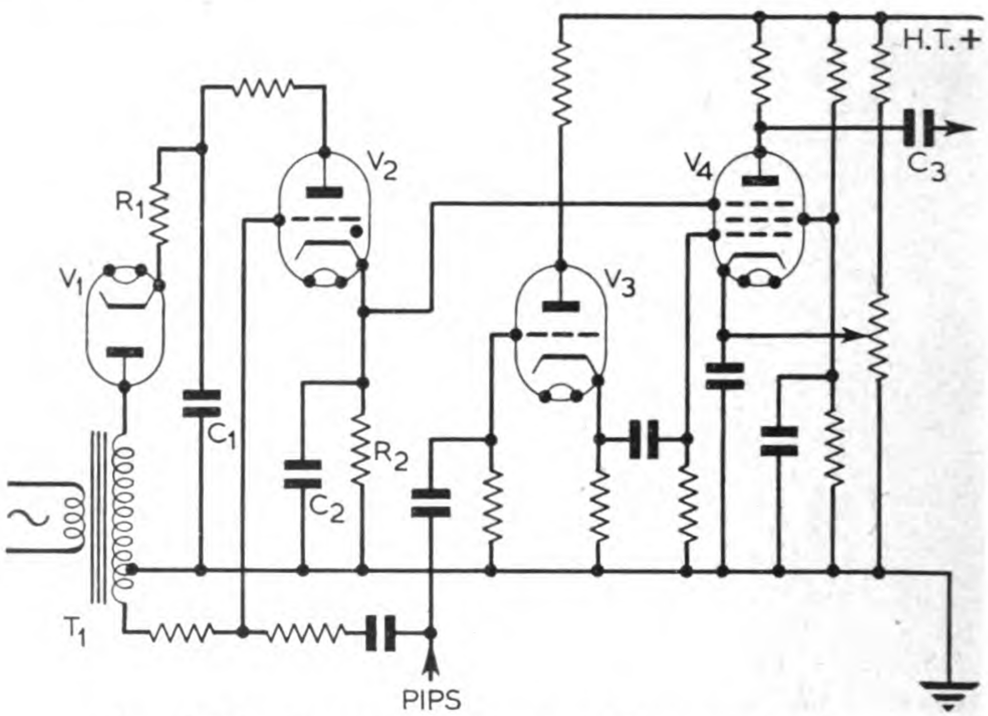

Fig. 15.6.—Crystal-controlled Trigger Circuit.

output (C_3). The first of these pips is used to trigger the modulator and timebase circuits, ensuring the required synchronism. C_1 discharges fairly rapidly so that only a few pips reach the output for each cycle of operation.

To avoid possible jitter which might occur if V_2 fired at nearly but not quite the same instant as a pip occurred, it is advisable to superimpose pips on the grid of V_2. This ensures that when the voltage on the grid has nearly reached the point at which the valve would fire in any case, it is then caused to fire by the pip. The time constant of C_2R_2 is made such that the voltage on the suppressor of V_4 does not rise quickly enough for the pip which triggered V_2 to get through V_4. The next pip is the one which triggers the modulator and timebase. To avoid interaction between the two circuits, the cathode follower V_3 acts as a buffer stage.

Crystal Oscillator Circuits

Circuits commonly used are shown in Fig. 15.7. In order that regeneration may occur and maintain oscillations it is necessary

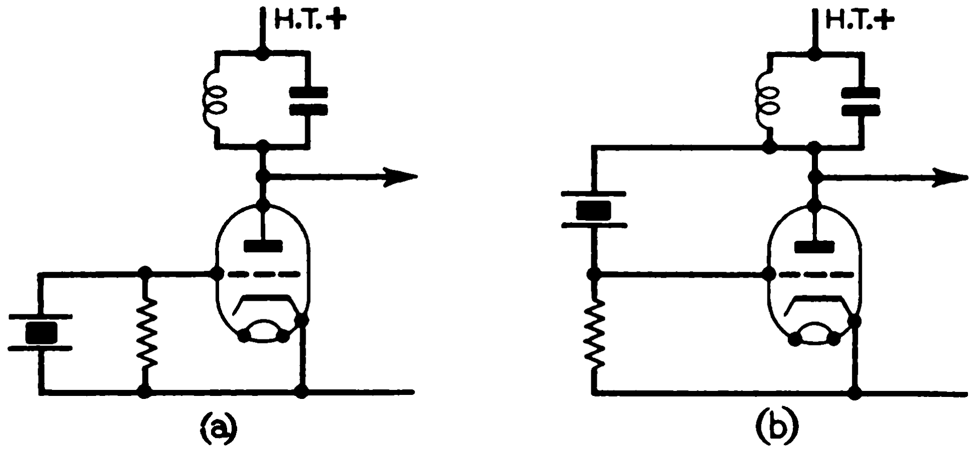

FIG. 15.7.—CRYSTAL-CONTROLLED OSCILLATOR.
(*a*) Grid-cathode connection.
(*b*) Anode-grid connection.

that the anode circuit be tuned to a frequency slightly higher than that of the crystal in case (*a*) and slightly lower in (*b*).

The output contains harmonics, and if a pure sine wave is required, as for example when used with a goniometer phase-shifting circuit, the output must be passed through one or more amplifying stages tuned exactly to the crystal frequency. The circuit shown in Fig. 15.8 may be used, where L_1C_1 and L_2C_2 are tuned slightly above and equal to the crystal frequency respectively. In this case, the screen of the pentode acts as anode for the oscillator part of the circuit.

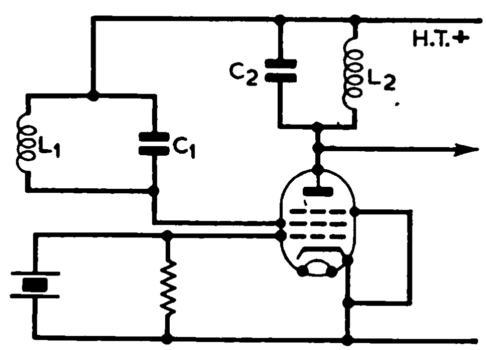

FIG. 15.8.—CRYSTAL-CONTROLLED OSCILLATOR WITH TUNED CIRCUIT FOR ELIMINATING HARMONICS.

Strobe Generating Circuits

Fig. 14.7 is really a form of strobe generating circuit. More complete circuits are shown in Figs. 15.9 and 15.10.

In Fig. 15.9 V_1 and V_2 are initially cut off. Application of a positive square wave to the grid of V_1 starts a Miller time-base, consisting of $R_1R_2C_1V_2$. The anode voltage of V_2 runs down until it reaches a potential determined by the setting of R_3. At this point V_4 begins to conduct and the voltage drop in the associated resistances lowers the potential of the grid

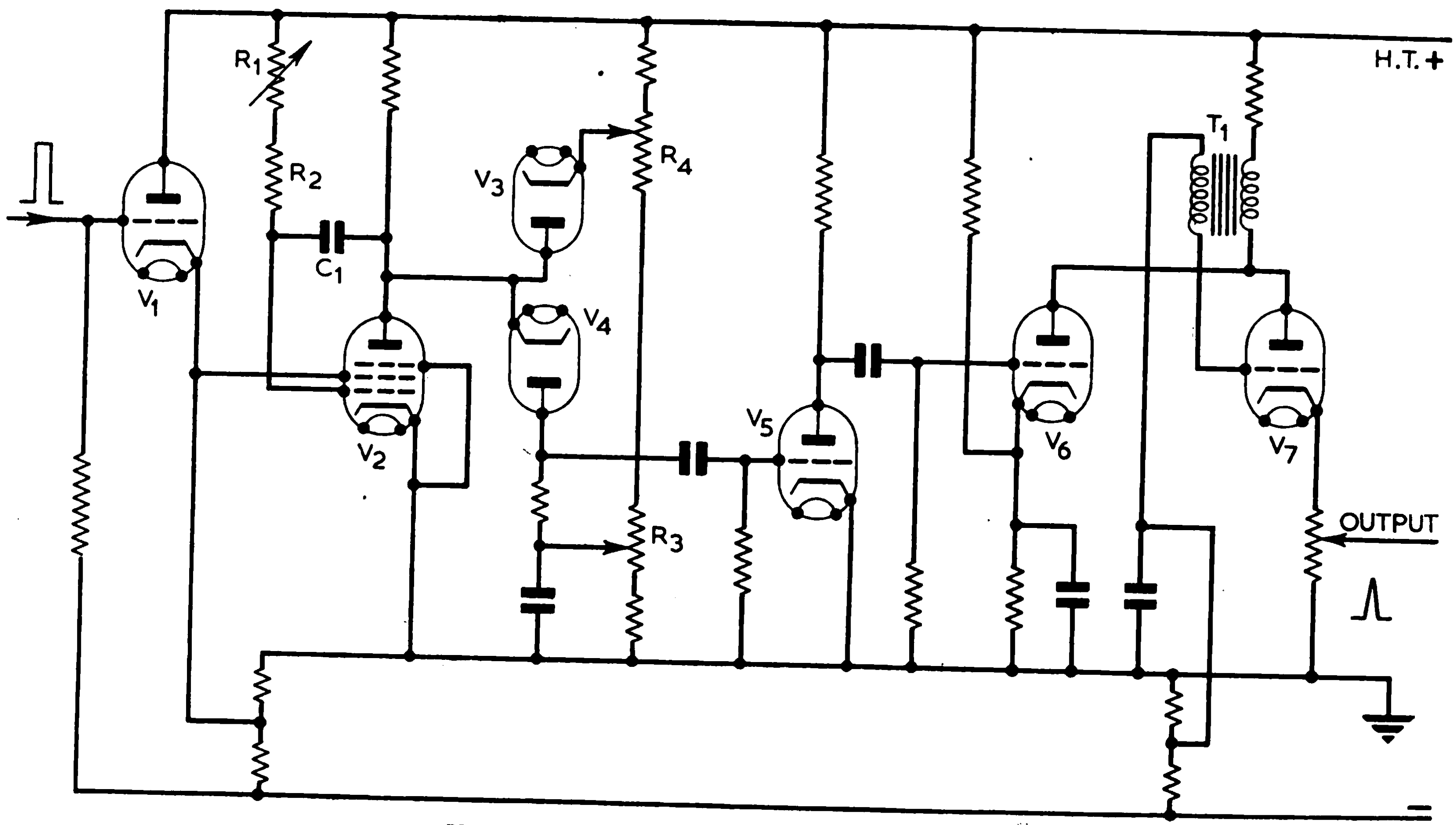

FIG. 15.9.—A STROBE GENERATING CIRCUIT.

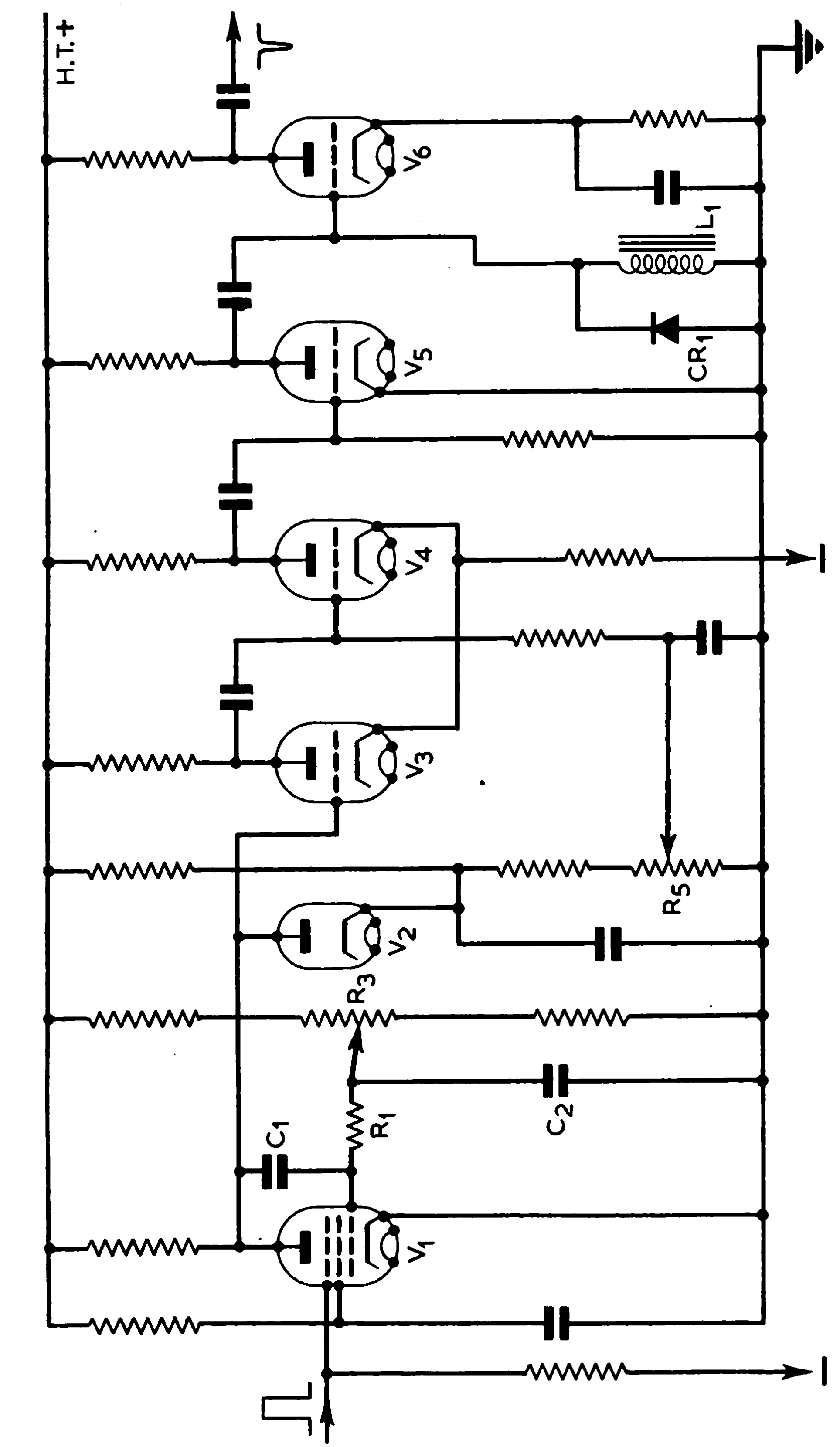

FIG. 15.10.—STROBE GENERATING CIRCUIT—ANOTHER EXAMPLE.

of V_5, producing a rise in voltage at its anode. This triggers the blocking oscillator T_1V_7 and produces a sharp positive pip in the cathode circuit of V_7. This pip is fed to the cathode-ray tube, where it produces a bright spot on the trace.

If a step strobe is required, the output of V_5 can be arranged to trigger a multivibrator, giving a square wave which can be applied to the deflection plate circuit. R_3 is calibrated to indicate range, and R_4 is a zero adjustment. The duration of the sweep is proportional to the difference of voltage between the two sliders (R_3 and R_4).

In Fig. 15.10 V_1 is initially cut off. V_3 and V_4 form a cathode-coupled flip-flop, V_4 being initially cut off.

A Miller timebase (C_1R_1, etc.) is started, as in the previous case, by a positive switching wave at the input. The rate of fall of potential at V_1 anode is controlled by R_3. As the voltage falls, the cathode of V_3 follows, taking V_4 with it until the latter begins to conduct. This happens at a point determined by the setting of R_5, and triggers the flip-flop, giving positive and negative square waves at the anodes of V_3 and V_4 respectively. Either of these may be used to give a step strobe. In the circuit shown, the negative wave cuts off V_5, producing a positive voltage on L_1 which begins to oscillate at high frequency with stray capacitance. Only one half-cycle occurs, for the next is damped out by the crystal CR_1. A negative-going pip is therefore produced at the output.

If the same circuit is used for speeding up part of the trace and also for producing the strobe, the latter event must be delayed a short time behind the former, in order that it may appear wholly in the speeded-up portion. This can be done by inserting a suitable delay circuit in the feed to the part of the circuit that actually produces the strobe.

The Phantastron

The circuit shown in Fig. 15.11, known as the " phantastron ", can be used for producing a rectangular pulse of known short duration. The trailing edge of this pulse can then be used to trigger another circuit, at a known time interval after the original trigger.

In the quiescent state the anode and grid potentials of the pentode V_1 are clamped to definite values by the diodes V_2 and V_3, screen current is flowing, and the resultant drop across R_5 is sufficient to raise the potential of the cathode to some value higher than that of the suppressor, so that the anode of V_1 is cut off.

The application of a positive trigger pulse to the suppressor allows anode current to flow. This produces a sudden drop of anode voltage, due to R_2, accompanied by a corresponding fall of grid voltage communicated through C_2. The cathode current falls to a value small enough to bring the cathode potential below that of the suppressor, and current continues

to flow, even although the trigger pulse may have ceased by this time.

V_1 with C_2 and R_3 constitute a Miller timebase, and the Miller

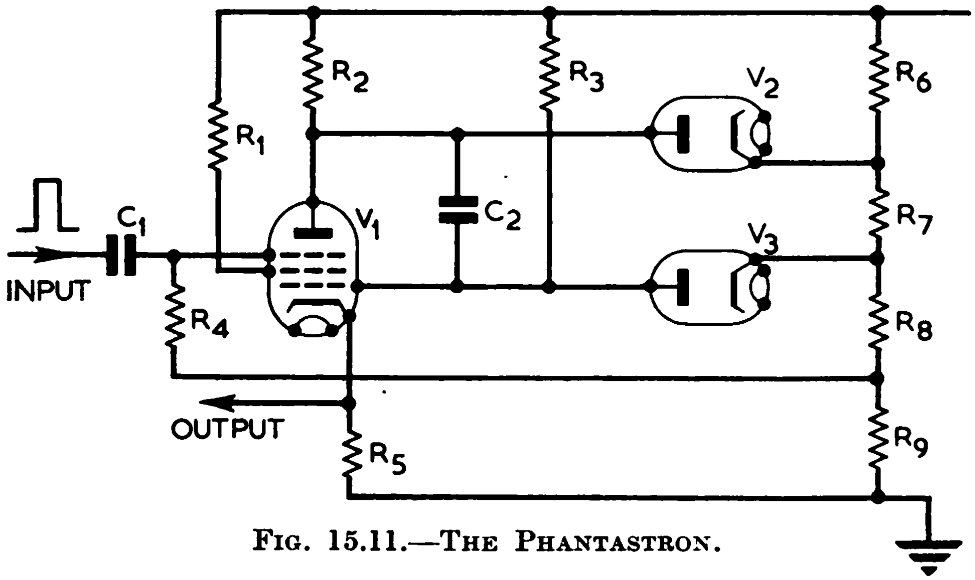

Fig. 15.11.—The Phantastron.

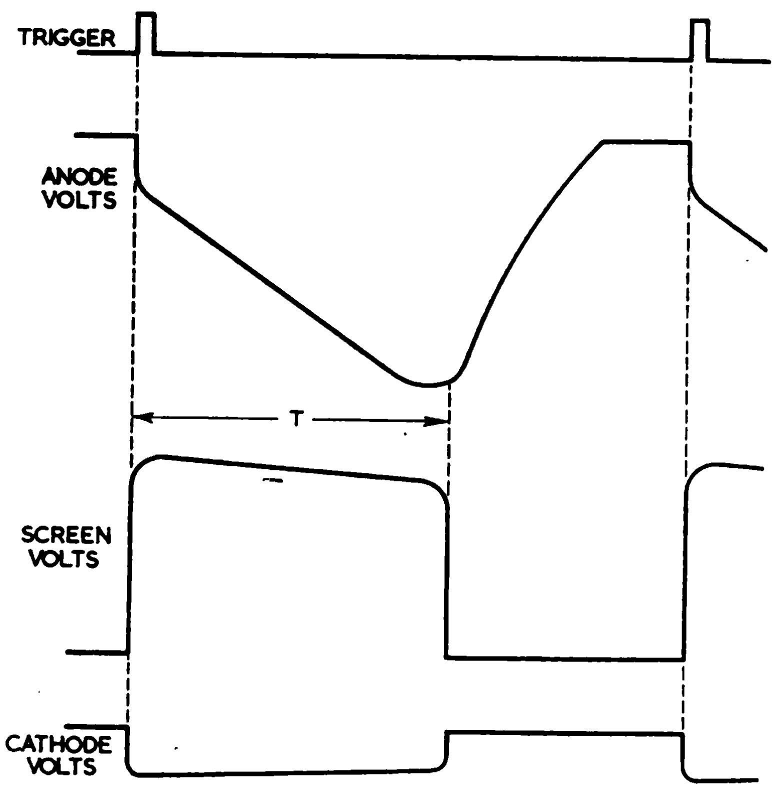

Fig. 15.12.—Phantastron Waveforms.

rundown now begins, the grid voltage, and consequently the cathode voltage, also rising linearly. When V_1 bottoms, the rate of rise becomes greater and a point is rapidly reached at

which the suppressor again begins to cut off the anode current. The resulting rise of anode voltage is communicated to the grid through C_2, and the action is therefore regenerative, causing the rise in anode voltage to be very rapid until the anode is again cut off. Thereafter the anode returns to its initial voltage exponentially by the charging of C_2 through R_2.

Waveforms are shown in Fig. 15.12. A trigger pulse can be taken from either screen or cathode of V_1, and will be produced at a time T after the application of the initial trigger.

Artificial Lines as Delay Circuits and Calibrators

The artificial line shown in Fig. 15.13 will give a delay between input and output equal to $n\sqrt{LC}$, where n is the number of sections.

If such a line is connected as shown in Fig. 15.14, the " output "

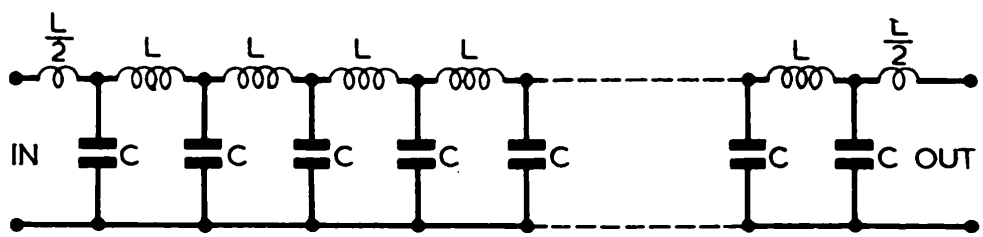

FIG. 15.13.—ARTIFICIAL LINE.

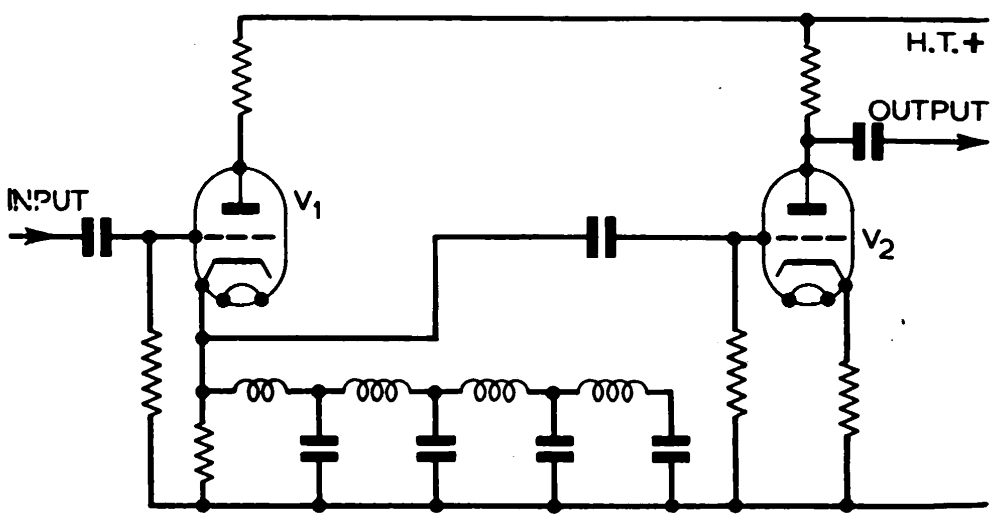

FIG. 15.14.—ARTIFICIAL LINE ARRANGED FOR PRODUCTION OF CALIBRATION PIPS.

end being open, and if there is sufficient mismatch between the line and the cathode resistor, a short sharp pulse applied to the grid of V_1 will be reflected backwards and forwards along the line, producing another pulse each time it reaches the input end, until the energy is dissipated. A series of pulses, spaced $2n\sqrt{LC}$ apart, is therefore obtained at the output of V_2.

This arrangement is an alternative to the ringing circuit.

Gateing Circuits

If a circuit is required to pass a signal only at certain times in a cycle of operations, a gate can be provided by passing the signal through a pentode which is cut off on its suppressor by suitable negative bias, except when a positive rectangular switching wave is applied to cancel the bias and allow the valve to conduct. Such circuits are required in connection with beam switching or split, with automatic following, the application of A.G.C. to a selected echo, and many other purposes. The required square wave may be generated by some form of multivibrator, or the phantastron may be used.

If, as with automatic following, for example, two gateing waves are required, the second beginning when the first ends, the trailing edge of the first can be used to trigger the second.

Supersonic Delay Cell for Ranging

A vertical tube containing water or other suitable liquid and provided with a piezo-electric crystal at the bottom and a movable plunger at the top can be used for measuring range.

A fraction of the transmitter pulse is fed to the crystal where it is converted into a supersonic pulse. This travels up the tube, is reflected from the plunger, and returns to the crystal at the bottom where it is converted into an electrical impulse.

The time taken for this to happen depends on the velocity of sound in the liquid, and the distance the sound wave has to travel, which depends on the position of the plunger.

The plunger can be moved until the delayed transmitter pulse is coincident in time with the relevant echo signal. From a knowledge of the path length in the tube and the velocity of sound, the range of the target can be calculated. As the velocity of radio waves is roughly 200,000 times the velocity of sound in water, a tube one metre long will suffice for targets up to ranges of about 200 kilometres.

A cathode-ray tube can be used for displaying the two pulses to enable the operator to adjust for coincidence.